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Corn and Sorghum Herbicides and Water Quality: An Evaluation of Alternative Policy Options

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Abstract

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Keywords

Agriculture, Agronomy, Policy, Water quality quantity and management, Weed control

Disciplines

Agricultural and Resource Economics | Agricultural Science | Agriculture | Agronomy and Crop Sciences | Natural Resources Management and Policy | Weed Science

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ABSTRACT

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CORN AND SORGHUM HERBICIDES AND WATER QUALITY: AN EVALUATION OF ALTERNATIVE POLICY OPTIONS

In February 1989, the President's Initiative on Water Quality proposed a vigorous national effort to protect groundwater and surface water from contamination by agricultural chemicals and wastes. As a part of this initiative the U.S. Geological Service analyzed surface water samples from 149 sites in 122 river basins in the midwestern United States (USGS 1991). These data indicated that large concentrations of herbicides were flushed from crop land and were transported through the surface water system as pulses in response to major rainfall events. Nearly 50 percent of the samples had concentrations of dissolved atrazine in excess of 3 parts per billion (μg/L), the drinking water Maximum Contaminant Level (MCL) for long-term exposure from atrazine. Belluck et al. (1991) note that the detection rate of atrazine is 10 to 20 times more frequent than the next most often detected pesticide. The detected levels, often exceeding the federal drinking water standard of 3 ppb, have led the EPA and state agencies to review policies to control or ban atrazine use.

In addition to water quality problems, atrazine poses hazards through air transport and food residues, and from exposure for applicators and wildlife. Even though there are water quality and other environmental concerns related to the use of atrazine and other agricultural chemicals, the economic value of these chemicals to producers is significant. Atrazine is the most widely used herbicide for weed control in corn and sorghum production. Current atrazine use in the Midwest is estimated at 52 million pounds of active ingredient, accounting for nearly 12 percent of the total agricultural pesticide use in the United States (USDA 1991).

Given the need to consider the complexity of water quality issues when assessing the risks and benefits of agricultural pesticide use, EPA funded the development of the Comprehensive Environmental Economic Policy Evaluation System (CEEPES) by Iowa State University's Center for Agricultural and Rural Development (CARD). CEEPES is an integrated modeling system used to estimate the economic and environmental consequences of alternative policies affecting pesticide use. Currently, CEEPES is the only available holistic system that is capable of evaluating the economic and environmental impacts of alternative restrictions on management practices and runoff standards.

The CEEPES system is an analytical framework designed to generate trade-offs for regulating nonpoint source reduction. It is currently configured to evaluate herbicide policies centered on the use of atrazine and 16 other major herbicides in the midwestern United States. The CEEPES study region includes the Corn Belt and Lake States regions, plus portions of the Northern Plains region and five other U.S. Department of Agriculture farm production regions (Figure 1). The region includes more than 80 percent of U.S. corn acreage and 30 percent of sorghum acreage. The system is constructed to evaluate policies regulating atrazine and triazine herbicide use on corn and sorghum.

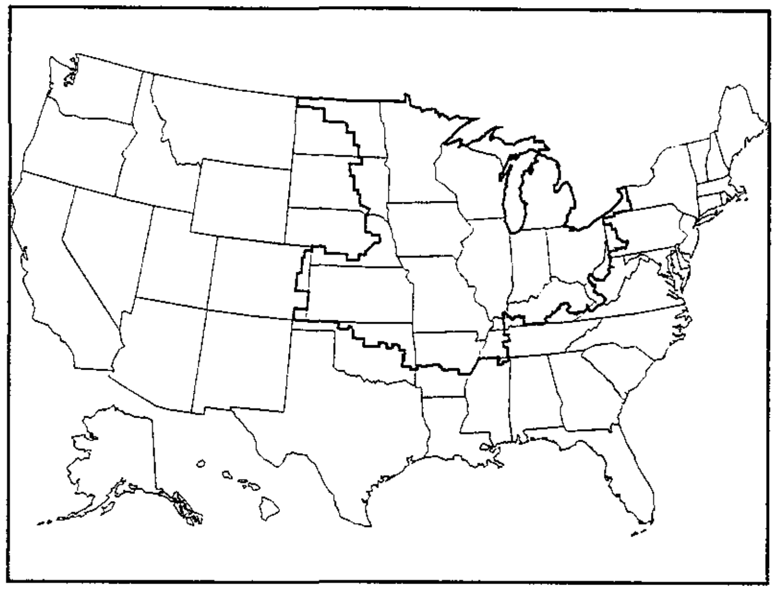

Figure 1. CEEPES study region for the atrazine analysis

One of the most important aspects of CEEPES is a detailed characterization of weed control technology, through alternative weed control strategies that allow evaluation of incentive- and standards-based policy options, in addition to policies like herbicide rate restrictions and bans. The CEEPES system is updated to characterize weed control strategies separately for predominantly sandy soils and predominantly clay soils, so there are 488 alternative weed control strategies constructed for corn and 148 strategies constructed for sorghum. These strategies are designed to control both grasses and broadleaf weeds.

Each strategy includes a primary and a backup treatment (to deal with weeds that survive the primary treatment), a set of herbicides applied individually or in tank mixes, a tillage practice (no, reduced, or conventional tillage), chemical application rates, an application mode (broadcast, incorporated, banded), a timing of application (early preplant, preplant incorporated, preemergent, postemergent), and temporal windows of application and effectiveness for both primary and secondary strategies. Thus, a ban on a particular herbicide does not simply imply a chemical-for-chemical substitution, but rather selection from among an entire array of weed control strategies that are potential substitutes. Weed control strategies have also been updated to reflect new information, including facts about the effectiveness of sulfonylurea herbicides. In addition, production risk is incorporated into the modeling system by simulating the impact of weather uncertainty on dates of chemical application and the resulting effectiveness. This approach is embodied in WISH (Weather Impact Simulation on Herbicides); see Bouzaher et al. (1992).

This report summarizes CEEPES evaluation of five different corn and sorghum herbicide policy options, including (1) a complete ban on the use of all triazines (triazine ban), (2) a complete ban on atrazine alone (atrazine ban), (3) a policy restricting annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to long-term MCL of 3 parts per billion (MCL restriction), (4) a policy restricting 24-hour acute concentration of atrazine in surface water to 10-day Health Advisory Level (HAL) of 100 ppb (HAL restriction), and (5) a policy of allowing only postemergent applications of atrazine on corn and sorghum (atrazine post restriction).

Because of conflicting interests from the use of corn and sorghum herbicides, particularly atrazine and other triazines, any information on alternative management practice and runoff standards that would minimize herbicide runoff and leaching without adversely affecting crop production and competitiveness of the farmers will be timely. A *management practice standard* is defined as a set of restrictions on the management practices the farmer may choose, while a *runoff standard* is defined as a restriction on the permissible value of concentration in surface water. According to nonpoint pollution theory, policies based on management practice incentives (taxes/subsidies) outperform management practice and runoff standards (Shortle and Dunn 1986). But this holds only under the restrictive assumption of zero transactions costs.

An extreme case of management practice standard would be to completely ban the use of herbicides that pose severe threat to the environment. The policy option banning a certain herbicide, say for example atrazine or all triazines, is not without limitations. By banning certain herbicides, substitute herbicides will come into wider use, imposing different environmental stress, cost or efficiency penalties, and shifts in production and resource use patterns.

The atrazine post restriction is considered as an alternative to a total ban on the use of atrazine. The idea is to eliminate atrazine use when there are substitute herbicides that may achieve similar levels of control, and allow the continued use of atrazine for postemergent application where substitute herbicides may not be as effective. This policy also shifts atrazine applications to a typically drier part of the season, reducing the potential for runoff. Unlike a complete ban or selective management practice restrictions, such as atrazine post restriction that does not allow any preplant or preemergent applications, the policies based on runoff standards are not straightforward.

CEEPES can provide spatial values of 24-hour acute (peak) surface water concentrations, (defined as the largest concentration over a 30-year simulation period) for the baseline use of atrazine and other herbicides. The annual average concentrations represent the average of the 30-year peak over four quarterly samples. Evaluating the peak and average spatial concentrations against the respective short-term and long-term benchmarks, the soils that introduce concentrations in excess of the benchmark can be targeted to achieve the runoff standard, which is the "direct" approach. Since the agricultural economic decision component of CEEPES is defined at the watershed level, which is a collection of several soils, it is not possible to target specific soil. However, it is possible to achieve the runoff standard indirectly by limiting the economic model's choice of weed control strategies. By eliminating those weed control strategies that may cause the surface water concentration of atrazine to exceed the benchmark, from any given soil, the runoff standards are achieved indirectly.

A drawback of this approach over the direct approach is that it eliminates the use of "risky" weed control strategies over all soils rather than the soil in which it is risky; therefore, this is a second-best option. Table 1 shows the number of atrazine-based weed control strategies that the agricultural decision model can choose from under alternative policy scenarios, including the baseline. This comparison indicates how intense the economic and environmental impacts of the alternative policy restrictions would be.

The results are aggregated over the entire study region, as shifts from the baseline (status quo), but they are available for states or for USDA farm production regions. It should also be noted that the policy impacts measured as relative shifts from the baseline are of more merit than absolute values. The results of the baseline, atrazine ban, and triazine ban are different from earlier results published in CARD Staff Report 93-SR 59 because of the modifications made to WISH. The major changes include decoupling sand and clay strategies and excluding sulfonylurea—primisulfuron (Beacon®). Some recommendations by weed scientists on herbicide efficacy have been incorporated, but information on crop injury has not been included because the necessary data are not yet available. We use the common chemical names of herbicides and their brand names interchangeably in this report. Figure A.1. cross-references the herbicides modeled and their brand names and also lists their

Table 1. Atrazine-based weed control strategies for alternative policies by crop and tillage

Crop/Tillage	Baseline			Restrictions		
	All Strategies	Atrazine-based Strategies	Triazine/ Atrazine Ban	MCL[a,b]	HAL[c,d]	Atrazine Post
Corn						
Conventional tillage	266	141	0	6	26	80
Reduced tillage	144	74	0	0	0	44
No-till	78	48	0	0	2	22
All	488	263	0	6	28	146
Sorghum						
Conventional tillage	75	50	0	3	28	22
Reduced tillage	51	32	0	2	21	15
No-till	22	18	0	0	3	7
All	148	100	0	0	52	44

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

benchmark values. Appendix B shows the shifts in weed control strategies for corn and sorghum under alternative policies.

The Four Components of CEEPES

CEEPES integrates diverse simulation models within four major components—policy, agricultural and economic decision, fate and transport, and health and ecological risk. Environmental policies relating to agriculture inherently reflect a trade-off between the need for production practices that minimize the costs of production and control of agricultural chemicals that are introduced into the environment by those practices. Unintended adverse environmental effects can even occur if policies to protect ground and surface water quality from pesticides result in increased soil erosion, and hence sediment loadings to, surface water. Therefore, it is essential that analytical tools allow policymakers to evaluate policies and practices both for the needs of commodity production and to protect the environment.

CEEPES simulates risk-benefit trade-offs associated with nonpoint source pollution from agricultural production. It links biophysical with economic modeling systems that have been integrated over the dimensions of time and space. Four components constituting the conceptual structure, illustrated in Figure 2, provide the necessary flexibility for model and policy integration. To ensure congruence of temporal and geographic scale, "experiments" with calibrated geophysical process models produced response surfaces (metamodels) that have statistical integrity and known experimental and sampling error (Bouzaher et al. 1993).

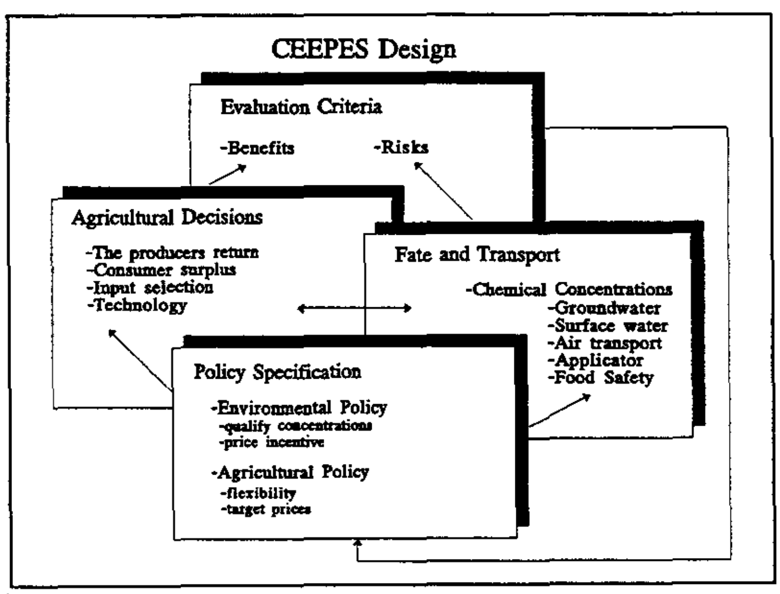

Figure 2. CEEPES design

Metamodeling is a novel statistical procedure that allows us to predict the impact of optimal agricultural production practices on water quality. Metamodeling abstracts away from unneeded detail for regional analysis by approximating outcomes of a complex mathematical process model through statistically validated response functions, which then allows alternative policy evaluations without additional simulations. Metamodels to predict herbicide concentrations in groundwater at 1.2 and 15 meters and surface water were fitted from 7,518 areawide simulations of corn and sorghum under alternative tillage practices and timing of herbicide applications. The areawide simulations captured the spatial heterogeneity (ubiquitous in nonpoint pollution processes) introduced by soil, hydrology, and weather using a statistically sampled distribution of these spatial parameters.

The information flow and configuration of the system are shown in Figure 3. Policy and regulatory options affect the range of strategies available to the producer. The system is configured to allow simulation of policy interventions restricting or enhancing producer behavior with regard to production decisions. The Resource Adjustment Modeling System (RAMS) is a linear programming model that simulates the profit-maximizing decisions of producers. Producers choose an optimal mix of crop and crop rotations, chemical inputs, labor, tillage, and other factors to maximize net return. The WISH model identifies the most efficient weed control strategies for corn and sorghum based on timing and method of application, efficacy of chemical combination, and tillage. Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) is a process model that simulates crop growth, weed competition, and the interactions of management alternatives. The fate and transport models estimate loadings and concentrations of contaminants in the various environmental media, such as water and air. These concentrations are then either summarized directly as a ratio to health or environmental benchmarks or as a frequency that a benchmark is likely to be exceeded under any estimated scenario. The models that compose the various components are described in detail in conjunction with the component in which they function.

Various factors influence the domain of natural phenomena to produce measurable outcomes of policy interest. A computer physical process model simulates the phenomenon for a specific environmental medium or activity. Because the time steps and area over which the phenomena are simulated by a model differ according to the medium or activity for which they occur, the outcomes generated by one model specific to a particular medium cannot easily be related to those of another. Therefore, integration of the system, whereby an economic activity is temporally and spatially linked with physical phenomena, involves: (1) consistently and robustly linking component models, and (2) aggregating the results into regional indicators of risk and benefits.

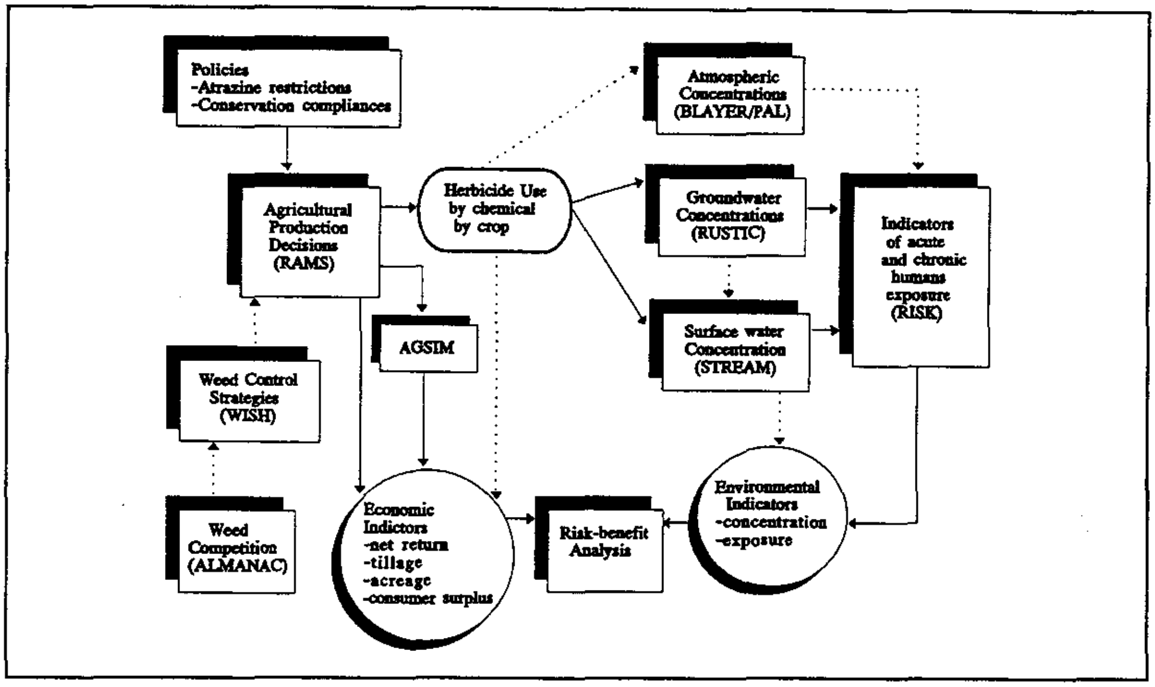

Figure 3. Information flow in CEEPES

Key problems that had to be overcome in applying CEEPES to a large region include the wide variation in temporal and spatial scales of different models requiring special interfaces; difficulties aggregating field-scale model output to larger geographic areas; the lack of adequate calibration and validation data for models; the lack of detailed data on chemical applications, yields, and producer risk; and the need for diverse soil and weather data sources. The consequence of these problems is that CEEPES is appropriately used only to analyze relative shifts in policy alternatives from the baseline. Improved coordination between USDA and EPA with regard to data specification and development could improve accuracy and facilitate the use of CEEPES for other crops and regions.

Environmental Fate Component

Chemical Leaching. Herbicide leaching in the soil root and vadose zones was simulated with the PRZM and VADOFT components of the EPA's RUSTIC (Risk of the Unsaturated/Saturated Transport and Transformation of Chemical Concentrations) model. The PRZM (Plant Root Zone Model) component of RUSTIC partitions the mass of the pesticide into amounts available for volatilization, runoff, and leaching. The amount available for leaching becomes the input into the VADOFT component that moves the mass from the root zone through the vadose zone. We did not estimate lateral flow with RUSTIC. Statistical sampling of soil, climatic, pest management, and chemical parameters representative of the study region were used as inputs to RUSTIC to estimate groundwater concentrations. Thus, using statistical procedures, we select a sufficient number of data for each key variable that affect the concentrations in groundwater to achieve the desired level of statistical accuracy and reliability. We then estimate peak and average pesticide concentrations at depths of 1.2 and 15 meters, which are assumed representative of vulnerable, shallow groundwater and are typical depths for the water table and rural domestic drinking water wells in the study area.

Chemical Runoff. Edge-of-field pesticide loadings from RUSTIC serve as input into the STREAM (Surface Transport and Agricultural Runoff of Pesticides for Exposure Assessment) methodology to estimate chemical concentrations in surface water. STREAM is a screening-level tool for estimating in-stream solution and stream bed concentrations. It is based upon 10-year simulation runs of the HSPF river basin model for representative watershed of four main crop producing areas. STREAM estimates are generally within a factor of 10 of actual monitoring values.

Agricultural Decision Component

Input Substitution Model. The WISH model simulates the efficacy and cost of alternative weed control strategies for corn and sorghum. It simulates likely weed control management based on herbicide efficacy, weather conditions, timing and effectiveness of application, mode of application, soil texture, targeted weeds, and observed farming practices. A detailed weed control subsector, constructed by feeding information from a 50-year simulation of WISH, linked to crop production through herbicide management practices, productivity response, resource use, and chemical cost is incorporated in RAMS to simulate substitution among weed control strategies.

Economic Behavior Model. RAMS integrates the information on policies affecting pesticide use and on farmer pest control strategies to simulate economic behavior for the system. It is a regional, short-term, profit-maximizing, linear programming model of agricultural production. The objective function of RAMS maximizes total returns from marketing and government programs net of total variable production cost including weed control cost. RAMS simulates behavior of a representative producer at the producing area (PA) level. PAs are hydrologic regions representing aggregated subareas defined by the Water Resources Council (1970). There are 105 PAs in the continental United States. The optimal agricultural production practices from RAMS, for each policy scenario, are then linked to the fate and transport models RUSTIC and STREAM through metamodels.

The results from RAMS are input into a national econometric model, AGSIM, developed by Robert Taylor of Auburn University (Penson and Taylor 1992), to estimate changes in measures of economic welfare such as producer income, domestic consumer effect, and government outlays. The AGSIM model ties together econometrically estimated demand and supply equations for major crops and livestock through market clearing identities. Thus, the model solves for the set of crop and livestock prices that simultaneously clear all markets in a given year for given exogenous factors.

Benefit-Risk Characterization

The chemical concentration levels found in surface and groundwater are transformed into a unitless measure of risk that we call an *exposure value*, whereby pesticide-specific benchmarks for human health and aquatic habitat are used to weight the relative importance of pesticide concentrations. The term *exposure value* is used to prevent confusing such values with estimates of absolute risk. Instead, their purpose is solely for comparing policies and practices and serving as rough indicators of water quality. Using a benchmark for environmental hazards, such as long-term MCL, 10-day HAL, or aquatic benchmark, the exposure value for each chemical is calculated as:

$$\textit{Exposure Value (hazard}-\textit{weighted exposure)} = \frac{\textit{predicted concentration}}{\textit{environmental benchmark}} .$$

The exposure value normalizes concentration levels, thereby allowing us to compare risks across herbicides and across policies. If the exposure value exceeds unity, the concentration exceeds the benchmark. This ratio of predicted concentration to human health or ecological benchmarks is used as the measure of risk of adverse impact from environmental exposure. The greater this ratio is, the greater the risk that we would predict for exposure to a particular pesticide. Any value approaching or exceeding unity is of concern. The decision maker must, using whatever chemical-specific information is available, determine whether or not the risk depicted in the baseline scenario is of sufficient magnitude to warrant action. CEEPES can only assist in determining whether or not any action or policy to address the risk in the baseline scenario is likely to improve or worsen the overall environmental impact.

Economic Impacts

The pesticide use data employed to calibrate (to define the boundaries of) baseline herbicide use in CEEPES were obtained from Resources for the Future (Gianessi and Puffer 1991). Baseline atrazine use estimated by CEEPES is approximately 37.6 million pounds active ingredient (a.i.) on corn and about 4.1 million pounds on sorghum (Table 2). The use of all triazines combined is about 70.2 million pounds a.i. for corn and 4.2 million pounds for sorghum. The RFF and CEEPES estimates differ because (1) the RFF data represent a single snapshot of herbicide use based on an annual survey, while the results in CEEPES represent average use over several years, and (2) the sulfonylurea herbicide nicosulfuron was introduced subsequent to the RFF survey and we assume its potential benefit is fully understood and adopted by producers.

Production

Changes in acreage and yields of major crops under the five policy restrictions are shown in Tables 3 and 4. In the baseline, corn and soybeans are grown on 72 and 44 million acres and yield an average of 109 and 36 bushels per acre. Under these herbicide policy options, corn grain acreage and yields are projected to decline, with soybean acreage and yields increasing. Except for the triazine ban policy, there was approximately a 2 percent decline in corn acreage and a 1 percent increase in corn yields. Under a triazine ban corn yields declined by 2.6 percent because most of the efficient (in terms of minimum yield loss and cost) weed control strategies are triazine based. Therefore, eliminating all triazine-based weed control strategies produced a significant reduction of corn yields, as well as sorghum yields. Because of the flexibility constraint in RAMS for yield-production balance, to minimize unprecedented deviation of crop production from historical levels, the acreage reduction under the triazine ban policy was less than the other four policies, since with a triazine ban corn yields fell by more than 2.5 percent.

Contrary to corn acreage changes, soybeans acreage increased by more than 3 percent under atrazine post, HAL, MCL, and atrazine ban policy restrictions and increased by 0.35 percent under triazine ban, and the yield increases were less than 0.3 percent across all five policy restrictions. Under a triazine ban more acres were fallowed, and there was a 2.5 percent increase in wheat acreage, which is the fourth major crop in the study region after corn, soybeans, and hay. These four crops account for 89 percent of the total crop acreage in the study area. Figure 4 illustrates the corn, soybean, hay, and wheat acreage changes under the five alternative policy restrictions. The atrazine

Table 2. Current use of atrazine and all triazines in the study region

Crop	Chemical	RFF 1991[*]	CEEPES[a] Baseline	NAPIAP Study[*b]
			million pounds a.i.	
Corn	Atrazine	39.9	37.6	50.6
	All Triazines	58.7	70.2	72.3
Sorghum	Atrazine	6.3	4.1	4.1
	All Triazines	6.3	4.2	4.1

[*]NAPIAP (1992) as references.

[a]Value reported is for the CEEPES study region.

[b]Value reported is for 12 midwestern states.

Table 3. Changes in crop acreage under alternative policies

		Bans		Restrictions		
Crop	Baseline	Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
	million acres			percent change		
Barley	5.22	0.00	0.00	0.00	0.00	0.00
Corn	72.46	-1.14	-2.35	-2.40	-2.38	-2.60
Cotton	1.23	0.00	0.00	0.00	0.00	0.00
Hay	52.71	-0.40	0.60	0.54	0.48	0.70
Oats	4.88	0.67	1.10	1.22	1.23	1.23
Sorghum	5.41	-1.97	-3.72	-2.37	2.18	-0.52
Soybeans	43.87	0.35	3.51	3.56	3.02	3.47
Summer Fallow	6.15	6.15	-2.04	-2.03	2.03	0.00
Sunflowers	1.05	0.00	-0.01	-0.01	0.01	0.00
Wheat	23.52	2.47	0.51	0.39	0.39	0.44

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

ban, atrazine post, MCL, and HAL policy restrictions produced almost similar impacts on crop acreage, with the runoff standard for short-term exposure (HAL restriction) producing the smallest changes in acreage.

By banning triazines, the cost of weed control in corn and sorghum production increased by $3 per acre (Table 5). The HAL and atrazine post restrictions produced the smallest increase in corn weed control costs ($0.50 and $0.61) per acre. Banning atrazine and other triazines for corn requires the use of more expensive weed control strategies to achieve a comparable level of control. In sorghum, banning atrazine and other triazines increased the dependence on more expensive but less effective weed control strategies. As a result, there were much higher reductions in sorghum yields than corn (Table 4).

Table 4. Changes in yields under alternative policies

			Bans		Restrictions		
Crop	Units	Baseline	Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
		units per acre				percent change	
Barley	bu.	48.2	0.00	0.00	0.00	0.00	0.00
Corn	bu.	109.1	-2.60	-1.19	-1.21	-1.07	-1.15
Corn Silage	tons	10.6	7.16	1.01	0.94	0.09	1.67
Cotton	bales	1.5	0.00	0.00	0.00	0.00	0.00
Legume Hay	tons	4.4	1.37	0.13	0.13	-0.20	0.52
Nonlegume Hay	tons	1.0	-1.38	-1.01	-0.85	-0.24	-1.84
Oats	bu.	52.6	0.28	0.12	0.00	-0.03	-0.01
Sorghum	bu.	79.9	-10.26	-3.43	-3.30	-2.79	0.42
Sorghum Silage	tons	11.4	-12.76	-0.50	-0.50	-0.45	-0.1
Soybeans	bu.	36.3	0.24	0.19	0.18	0.29	0.21
Sunflowers	cwt.	13.2	0.00	0.01	0.01	0.01	0.00
Spring Wheat	bu.	32.0	1.06	0.17	0.17	0.17	0.18
Winter Wheat	bu.	56.1	-1.18	0.02	0.05	0.06	0.05

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

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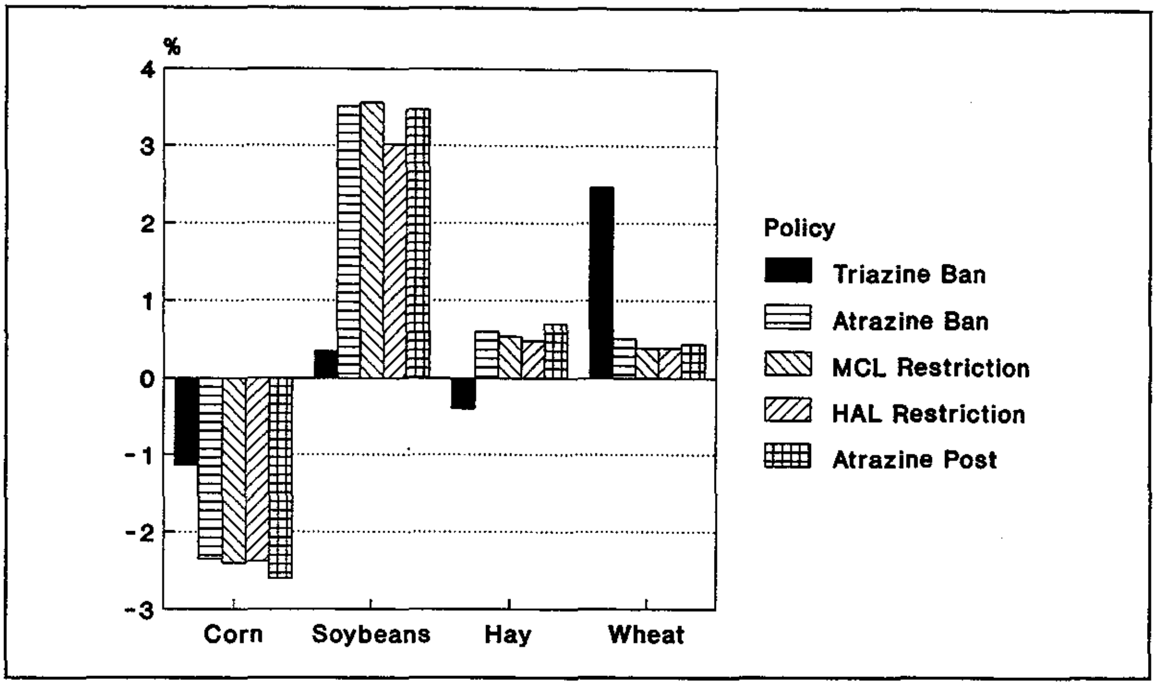

Figure 4. Percentage changes in the acreage of major crops

Table 5. Changes in cost of herbicide treatment under alternative policies

Crop	Baseline	Bans		Restrictions		
		Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
				change in dollars		
Corn	10.80	3.09	1.08	0.89	0.50	0.61
Sorghum	8.55	3.04	3.10	2.84	2.31	1.49

[a]Restriction of annual average (over 4 quarters of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

Average per acre herbicide use and the number of acres of corn and sorghum treated are shown in Tables A.1. and A.2. Nearly 54 million acres of corn were treated with atrazine in the baseline. Cyanazine and simazine, the other two triazine herbicides, were used in treating 38 and 8 million acres of corn. Major substitute herbicides for atrazine and other triazines in corn production are dicamba, bromoxynil, metolachlor, alachlor, and 2,4-D. Under the four atrazine-based policy restrictions, corn acres treated by metolachlor increased by about 21 percent, except for atrazine post restriction, which produced only a 3 percent increase.

For alachlor, the increase was about 37 percent, except for atrazine post restriction, which produced a 17 percent increase in alachlor treated corn acres. Under a triazine ban, corn acres treated by metolachlor and alachlor increased by more than 75 percent. With the exception of an atrazine post restriction, corn acres treated by dicamba and bromoxynil increased significantly. The decrease in corn acres treated by dicamba and bromoxynil under an atrazine post restriction is because atrazine post strategies mostly come as tank mixes with either dicamba or bromoxynil. Herbicide substitution effects for corn and sorghum are measured by the changes in the herbicide acre treatment shares of alternative herbicide strategies for each of the policy restrictions (Appendix B).

Table 6 summarizes total corn and sorghum herbicide use in the study region. Except for the policy of banning all triazines, overall use of corn herbicides declined by 1 to 2 percent; the HAL restriction produced the largest reduction in total herbicide use (2 percent). By banning all triazines, the use of nontriazine substitutes increased significantly (215 percent), thereby increasing total corn herbicide use by 31 percent. Atrazine post restriction decreased atrazine use on corn by 90 percent compared to 79 percent under HAL restriction and 99.9 percent under MCL restriction. This suggests that the producer's economic impact from atrazine post restriction would be greater than HAL restriction. Because of the substitution of triazines with non-triazines the direction and the magnitude of the environmental impacts are not straightforward without further evaluation using environmental metamodels.

Economic Welfare

The welfare measures associated with yield and cost impacts of restricting atrazine and all triazines were estimated using the AGSIM Model. Table 7 presents both short-term (1993-96) and long-term (2005-08) welfare effects, including producer income, domestic consumption, foreign consumption, and government outlays. In the short term, average annual decreases in total economic welfare would be about $160 million under the atrazine post and HAL policy restrictions, and about $230 to $240 million under the MCL and atrazine ban policy restrictions. By banning all triazines the average annual decreases in total economic welfare was three times greater than the other four policies; however, there was a 3 to 4 times greater reduction in government outlays because of a 7 percent increase in corn price (see Table 8), which reduced deficiency payments. The short-term economic impacts of MCL restriction were comparable to the impacts produced by an atrazine ban

Table 6. Changes in herbicide use

			Bans		Restrictions		
Chemical	Crop	Baseline	Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
		mil. lb.			percent change		
Atrazine	Corn	37.6	-100.00	-100.00	-99.91	-78.84	-90.72
	Sorghum	4.1	-100.00	-100.00	-87.60	-25.58	-43.95
All Triazines	Corn	70.2	-100.00	-20.16	-19.10	-20.60	-16.50
	Sorghum	4.2	-100.00	-65.57	-53.62	-13.90	-32.16
Nontriazines	Corn	50.2	214.63	25.56	25.64	24.14	21.15
	Sorghum	4.5	102.37	85.61	83.68	55.69	42.66
All Herbicides	Corn	120.4	31.11	-1.11	-0.46	-1.96	-0.81
	Sorghum	8.7	5.20	13.02	17.75	22.28	6.73

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

policy. Unlike atrazine post restriction, the short-term economic impacts of HAL restriction were distributed across the board (producers, consumers, government). Atrazine post restriction produced smaller domestic consumer effects and also the least reduction in government outlays because of the smallest increase in corn price (0.4 percent).

Long-term impacts may not be as meaningful for the current analysis because no information was included on new, potentially more effective, weed control technologies like biological controls or new chemical substitutes. The long-term impacts of these policies were different from the trends noticed in the short term. Both the triazine ban and the atrazine ban produced more severe reductions in total economic welfare, $993 million and $458 million. Even though the short-term MCL restriction was as severe as banning atrazine, in the long term it reduced total economic welfare by 25 percent less. Except for the triazine ban, the producers bore the brunt of the economic impact in the short term, while in the long term it was the consumers who had to bear the larger share of the total economic impact. By banning all triazines, however, it was the consumer who was affected the most both in the short and long terms. In the short term consumer surplus fell as little as $19 million under atrazine post restriction to as much as $751 million under a triazine ban, compared with annual domestic food expenditures of $655 billion (ERS 1992). While expenditures and surplus measures are not directly comparable, expenditures do provide perspective. In terms of equitable distribution of welfare impacts across the board, runoff standard-based policy restrictions (MCL and HAL restrictions) fared better over the other three policies.

Table 7. Aggregate economic effects

	Bans		Restrictions		
Economic Effects	Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
			million dollars		
Short-term effect					
Producer income	-716	-269	-250	-200	-204
Domestic consumer	-751	-188	-168	-124	-19
Foreign consumer	-421	-70	-87	-65	-1
Government outlays	(-1124)	(-287)	(-273)	(-227)	(-65)
Total	-764	-240	-232	-162	-159
Long-term effect					
Producer income	-391	-207	-78	-53	-50
Domestic consumer	-530	-412	-243	-192	-193
Foreign consumer	-267	-87	-103	-83	-52
Government outlays	(-195)	(-248)	(-85)	(-75)	(-1)
Total	-993	-458	-339	-253	-294

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

Price

Table 8 shows the corresponding commodity price effects both for the short and the long term. Corn price increased by as much as 7 percent under a triazine ban compared to about 1 to 2 percent under the other four policies. The price of soybeans fell by 1 percent in the short term and 2 percent in the long term under triazine ban and by 0.26 percent under an atrazine ban. Under MCL, HAL, and atrazine post restrictions the price of soybeans fell in the short term and slightly increased in the long term. The price of hay increased in both time frames, except under atrazine post restriction. Wheat price decreased under all policies except the triazine ban.

Environmental Impacts

Environmental indicators, including soil erosion, complete the picture of the welfare impacts of these alternative policy restrictions. Since a single average indicator of water quality across the study region would be almost meaningless, we present results indicating *relative risk* to human beings and ecosystems, and the spatial distribution of these indicators identifying the most vulnerable soils (hot spots), which is useful for targeting. In addition, results are separated by surface water and groundwater.

Tillage has significant impacts on soil erosion and water quality. Conventional wisdom is that the soil conserving tillage practices, such as reduced and no-till, require more herbicide use for weed control. Table 9 shows the share of the three tillage practices in the baseline for corn, sorghum, and all crops, and the changes in those shares under various policy restrictions. By banning all triazines, the proportion of corn acres with no-till decreased by 2 percent, while under the remaining policy restrictions corn acres with no-till decreased by 1 percent. However, the net tillage adjustments over all crops were zero because of conservation compliance. Table 10 shows the impacts of alternative tillage practices on soil erosion. Note that the policy runs are performed with conservation compliance provisions enforced in the economic model; therefore, soil erosion impacts were minimal.

The peak and average chemical concentration levels found in surface and groundwater are transformed into a unitless measure—exposure value—whereby pesticide-specific benchmarks for human health and aquatic habitat are used to weight the relative importance of pesticide concentrations. Since pest control strategies often need more than one pesticide in a tank mix, and since different farmers use different strategies (and pesticides), surface and groundwater may contain a mixture of pesticides at any given time. Surface and groundwater may also contain a mixture of

Table 8. Price effects on selected commodities

Crop	Bans		Restrictions		
	Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
			percent change		
Short-term					
Corn	6.99	1.83	1.71	1.43	0.40
Sorghum	10.59	2.42	2.08	1.70	-0.20
Soybeans	-0.98	-0.26	-0.22	-0.31	-0.20
Oats	0.37	-0.23	-0.10	-0.03	0.10
All hay	1.26	0.37	0.42	0.24	-0.60
Wheat	1.37	-0.07	-0.08	-0.12	-0.20
Barley	-0.14	-0.01	~0.0	-0.01	~0.0
Cotton	-0.10	-0.06	0.05	0.05	~0.0
Long-term					
Corn	7.02	2.25	1.66	1.47	1.10
Sorghum	15.89	3.16	2.69	2.22	0.10
Soybeans	-2.08	-0.26	0.11	-0.04	0.50
Oats	-1.33	0.10	0.28	0.32	-0.20
All hay	1.27	0.57	0.48	0.25	-0.60
Wheat	0.52	-0.09	-0.16	-0.18	-0.20
Barley	-0.40	-0.86	-0.30	-0.30	-1.00
Cotton	1.27	0.01	-0.05	-0.04	0.10

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

pesticides where a variety of pest control strategies has been used over a number of years. For the purpose of comparing policy alternatives, we characterize the risk associated with exposure to these pesticide mixtures in a particular medium by adding the exposure values (the ratios of predicted concentrations to benchmarks for each pesticide in the mixture), in accordance with EPA guidelines on assessing risk from chemical mixtures (U.S. EPA 1992). A final risk value for a category of

Table 9. Changes in estimated proportion of acreage under different tillage practices

			Bans		Restrictions		
Tillage	Crop	Baseline	Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
						change	
Conventional	Corn	0.58	0.05	-0.01	0.00	-0.00	-0.01
	Sorghum	0.46	-0.46	-0.01	0.09	0.00	0.03
	All Crops	0.69	0.00	0.00	0.00	0.00	0.00
Reduced							
	Corn	0.36	-0.03	0.02	0.01	0.01	0.02
	Sorghum	0.54	0.34	0.01	0.09	0.03	0.00
	All Crops	0.28	0.00	0.00	0.00	0.00	0.00
No-till	Corn	0.05	-0.02	-0.01	-0.01	-0.01	-0.01
	Sorghum	0.00	0.12	0.00	0.00	0.00	0.00
	All Crops	0.03	0.00	0.00	0.00	0.00	0.00

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

Table 10. Impacts of tillage on soil erosion

		Bans		Restrictions		
Tillage	Baseline	Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
	million tons			percent change		
Conventional	754.27	-3.26	-0.57	-0.39	0.47	-0.39
Reduced	219.01	3.49	1.29	1.42	-0.26	0.80
No-till	5.82	-15.57	-15.52	-15.52	-6.84	-13.76

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

environmental impacts, human health as opposed to ecological, for a particular policy is determined by assigning a weight, or a measure of relative importance, to each medium of exposure or type of impact.

Two caveats are important to note before interpreting the environmental and water quality impacts of herbicides under alternative policies. First, more reliance should be placed on exposures rather than concentrations and on relative differences rather than absolute values. Second, surface water concentrations are simulated measurements from "in-stream" flow calculated from the "edge-of-field" loading given by RUSTIC, and are considered to be accurate within an order of magnitude and typically over estimate actual concentrations. A major assumption underlying the STREAM approach that every field lies adjacent to a stream, without accounting for "buffer effects" of other fields, riparian zones, and so forth, leads to overestimation. Furthermore, STREAM does not account for decay, soil adsorption, or other chemical processes that often occur in actual chemical runoff between a field and a water body, so eventually it over states surface water concentrations.

The human and aquatic exposure values from 24-hour peak surface water concentrations, from peak and average groundwater concentrations, and from the soil loss index are summarized for each policy restriction, including the baseline. For the set of weed control strategies, herbicide use levels, and the acres of crop activity projected by the economic model the media-specific herbicide concentrations were calculated using the environmental metamodels developed from RUSTIC and STREAM output. This output was simulated over 30-year historical weather patterns and a statistically sampled distribution of spatial, hydrological, chemical, and management parameters.

For each herbicide, the 24-hour peak surface water concentrations were calculated by individual soil types. These spatial concentrations were evaluated against the 10-day HAL for short-term exposure to identify soils with the potential to exceed the benchmark. The aggregate area of "at-risk" soils were adjusted by the policy-specific herbicide treated corn acreage distribution, and is expressed as percentage of at-risk corn acres relative to the total corn acres treated under each policy for each chemical (Table 11). For example, the first row in Table 11 shows that about 8 percent of corn acres would have 24-hour acute concentrations of atrazine in surface water exceeding the 10-day HAL of 100 ppb under baseline conditions. The percentage of at-risk corn acres is reported separately for acres of atrazine applied at a rate greater than 1.5 pounds a.i. per acre and for atrazine applied at a rate less than 1.5 pounds a.i.

Table 11. Percentage of at-risk corn acres treated with herbicides under alternative policies

Chemical	Baseline	Bans		Restrictions		
		Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
			percent			
Atrazine >1.5 lb	7.83	0.00	0.00	0.00	0.00	2.37
Atrazine <1.5 lb	23.67	0.00	0.00	0.00	0.00	0.00
Cyanazine	12.46	0.00	14.65	14.60	14.86	17.76
Bentazon	3.62	22.01	5.07	5.17	5.05	6.01
Metolachlor	1.86	2.16	0.86	0.87	0.85	1.38
Alachlor	8.44	2.06	3.77	3.77	3.75	2.90
Simazine	34.99	0.00	38.46	39.29	32.39	38.50

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

Notes: Risk measured as 24-hr acute surface water concentration exceeding the 10-day HAL. Chemicals not appearing in the table imply zero at-risk acres.

Under an atrazine ban, MCL, HAL, and atrazine post restrictions, the percentage of at-risk corn acres treated with cyanazine, simazine, and bentazon increased by 3 to 5 percent, while the at-risk corn acres treated with alachlor and metolachlor decreased. By banning all triazines, the at-risk corn acres are projected to decline for all chemicals except bentazon. In the case of groundwater, herbicide concentrations were below the benchmarks for all soils under all policies, including the baseline, implying zero at-risk acres.

Table 12 shows the relative impacts of alternative policies on soil erosion, groundwater and surface water quality, and ecosystem risk. There was very little impact on soil erosion mainly because of conservation compliance and also due to regional aggregation, which smoothed out interregional and other spatial impacts. The water quality impacts are evaluated by two types of exposure values: (1) the cumulative exposure value, which is a total of individual herbicide exposure values weighted across tillage and crop for a given medium, and (2) the largest exposure value (of

Table 12. Relative impacts on soil erosion, ground and surface water quality, and ecosystem

			Bans		Restrictions		
Medium	Ref. Benchmark	Baseline	Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
Soil erosion	Change (baseline)	1.00	0.9818[e]	0.9974[e]	0.9993[e]	1.0026[e]	0.9978[e]
Groundwater, 1.2m (peak)	10-day HAL	0.1122/ 0.0554	0.0021/ 0.0018	0.667/ 0.0609	0.0068/ 0.0067	0.0067/ 0.0065	0.0717/ 0.0610
Groundwater, 1.2m (avg.)	Long-term HAL	0.3633/ 0.2591	0.0489/ 0.0415	0.0125/ 0.0117	0.0012/ 0.0011	0.0014/ 0.0011	0.0489/ 0.0415
Groundwater, 15m (peak)	10-day HAL	0.0008/ 0.0005	0.0001/ 0.0001	0.0005/ 0.0005	0.0001/ 0.0001	0.0001/ 0.0001	0.0005/ 0.0005
Groundwater, 15m (avg.)	Long-term HAL	0.0161/ 0.0118	0.0000/ 0.0000	0.0006/ 0.0005	0.0000/ 0.0000	0.0000/ 0.0000	0.0047/ 0.0045
Surface water (peak)	10-day HAL	2.2218/ 0.8893	0.0436/ 0.0249	1.6756/ 0.8950	0.0370/ 0.0242	0.0359/ 0.0225	1.7715/ 0.8975
Ecosystem risk	Aquatic	32.47/ 8.84	1.95/ 0.63	26.87/ 8.86	26.57/ 8.26	26.54/ 8.22	27.95/ 9.16

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

[e] This policy run is performed with conservation compliance enforced in the economic model.

Note: The first number in a cell represents the weighted sum (weighted across tillage and crop—corn and sorghum) of the pesticide exposure values for a given medium and the second number is the largest exposure value for any pesticide predicted in a medium.

any single herbicide). This table also reports the reference benchmark used in evaluating the herbicide concentrations in each medium.

Under the triazine ban, MCL, and HAL policy restrictions, cumulative exposure as well as the largest exposure decreased significantly in all media and across all reference benchmarks. An atrazine ban would, in fact, increase the impact of short-term (acute) exposure from alternative herbicide use in corn and sorghum in shallow groundwater, and also the impact of short-term exposure from a single herbicide increase. Acute risks could increase slightly with the use of other triazines that are less persistent. A triazine ban would reduce significantly the acute, chronic, and aquatic risks as herbicides that tend to leach less or are less persistent are substituted. There would be more tilling to control weeds (Tables B.2 and B.8) and more conventional tillage (Table 9), relative to baseline. Under atrazine post restriction the acute impact from a single herbicide increased, suggesting a heavy substitution of other triazine herbicides, particularly simazine (Table A.2).

Conclusions

CEEPES analysis of policies restricting the use of atrazine and other triazines to achieve desirable water quality standards provides a number of key conclusions and observations. First, in the short term there will be a $764 million total economic welfare loss with a triazine ban and a significant reduction in government outlays on commodity programs and deficiency payments. With all other policies there will be only 1/3 as much economic welfare loss. Second, corn acreage reductions are substituted by soybeans and to a small extent, by hay and wheat. Third, the overall herbicide use on corn declined by only a small percent (1 to 2 percent), but with a complete ban on all triazines the overall herbicide use increased 31 percent. Fourth, herbicide policy restrictions shifted corn production away from no-till by 1 to 2 percent. However, keep in mind that an important assumption underlying this analysis is that farmers will not opt out of commodity programs. If farmers leave the commodity programs, they are no longer required to comply with conservation provisions on highly erodible land. The loss of atrazine and other triazine herbicides could lead to greater reversion to conventional tillage practices. More widespread conventional tillage would, in turn, lead to greater soil erosion and water quality problems from runoff.

As far as environmental impacts from water quality benefits, except for banning all triazines, there were no significant water quality improvements with banning or restricting the use of atrazine alone. With an atrazine ban, in particular, acute impacts to shallow groundwater from other triazine and nontriazine herbicides increased. Although in general exposure to herbicides in groundwater and surface water would decline and would be of lower general health concern than under the status quo, there could be an actual increase in at-risk site-specific acres exposed to other triazine and nontriazine herbicides. Although banning all triazines produced desirable environmental benefits, the economic costs are significantly larger and deprive producers of their competitive edge. On the other hand, the overall goal of reducing environmental risk with the least economic welfare loss would not be achieved through an atrazine ban either, unless producers are encouraged to adopt environmentally sound practices. The runoff standards-based policy restrictions and atrazine post restriction seemed to offer some promise for minimizing environmental risks with the least welfare reduction, but the current analysis assumes zero transaction costs, namely zero cost of monitoring and enforcement.

APPENDIX A. CEEPES HERBICIDES AND BENCHMARKS

Code	Chemical	Trade Name	MCL	Lifetime Health Advisory	10-day Health Advisory	Aquatic Benchmark
					(ppb)	
LAS	Alachlor	Lasso	2	2	100	1
ATR	Atrazine	AAtrex	3	3	100	2
BAS	Bentazon	Basagran	-	20	25	1
BUC	Bromoxynil	Buctril	-	140	700	1
SUT	Butylate	Sutan	-	50	2400	1
BLA	Cyanazine	Bladex	-	9	100	2
BAN	Dicamba	Banvel	-	9	300	1
ERA	EPTC	Eradicane	-	175	875	1
ROU	Glyphosate	Round-up	-	700	20000	60
DUA	Metolachlor	Dual	-	100	100	1
ACC	Nicosulfuron	Accent	-	44	44	0.03
PRO	Pendimenthalin	Prowl	-	300	1400	1
BEA	Primisulfuron	Beacon	-	210	210	0.03
RAM	Propachlor	Ramrod	-	70	350	1
PRI	Simazine	Princep	-	35	50	500
TFD	2,4-D	2,4-D	70	70	1100	1

Figure A.1. Herbicides included in CEEPES configuration

Table A.1. Changes in average per acre herbicide use under alternative policies

Chemical	Crop	Baseline	Bans		Restrictions		
			Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
		lb. a.i. per acre			percent change		
Atrazine > 1.5 lb/a	Corn	0.83	-100.00	-100.00	-97.97	-88.93	-75.47
	Sorghum	2.14	-100.00	-100.00	-100.00	-36.91	-100.00
Atrazine < 1.5 lb/a	Corn	0.66	-100.00	-100.00	-100.00	-11.29	-100.00
	Sorghum	0.82	-100.00	-100.00	-55.08	-24.92	-19.05
Nicosulfuron	Corn	0.01	157.17	10.27	9.41	17.75	33.20
	Sorghum	0.00	0.00	0.00	0.00	0.00	0.00
Dicamba	Corn	0.04	103.96	1.93	4.48	8.79	15.64
	Sorghum	0.06	104.07	57.68	58.88	59.40	41.18
Cyanazine	Corn	0.54	-100.00	48.53	49.73	29.94	56.18
	Sorghum	0.76	-100.00	-2.11	-2.18	-9.27	-9.36
Bromoxynil	Corn	0.01	39.08	6.26	5.79	-2.40	19.12
	Sorghum	0.06	57.55	-28.70	-23.28	11.80	11.81
Bentazon	Corn	0.04	-19.01	-6.21	-5.42	-43.65	-12.54
	Sorghum	0.05	41.95	-31.64	-26.41	13.69	13.70
Metolachlor	Corn	0.72	-42.35	-22.06	-22.06	-22.45	-24.41
	Sorghum	1.14	-54.25	12.87	7.76	0.10	3.89
EPTC	Corn	0.00	0.00	0.00	0.00	0.00	0.00
	Sorghum	0.00	0.00	0.00	0.00	0.00	0.00
Alachlor	Corn	0.72	-17.22	-15.45	-15.45	-16.29	-16.26
	Sorghum	0.89	-59.95	35.31	35.14	37.80	26.75
Simazine	Corn	1.52	-100.00	14.58	14.61	2.73	16.16
	Sorghum	0.00	0.00	0.00	0.00	0.00	0.00
Pendimethalin	Corn	0.06	-100.00	213.80	209.96	174.42	383.81
	Sorghum	0.70	-100.00	-100.00	-93.97	-77.82	4.40
Propachlor	Corn	2.12	-100.00	-100.00	-100.00	-100.00	-100.00
	Sorghum	1.93	11.36	-26.51	-25.62	-28.07	-27.69
Glyphosate	Corn	0.00	*	0.00	0.00	*	0.00
	Sorghum	0.85	3.01	0.00	0.00	0.00	0.00
Butylate	Corn	2.04	-5.93	-5.68	-5.67	-5.53	-6.85
	Sorghum	0.00	0.00	0.00	0.00	0.00	0.00
2,4-D	Corn	0.06	357.86	132.21	126.02	180.99	320.78
	Sorghum	0.08	18.66	88.60	116.33	29.47	129.55

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

Table A.2. Changes in acres treated under alternative policies

			Bans		Restrictions		
Chemical	Crop	Baseline	Triazine	Atrazine	MCL[a,b]	HAL[c,d]	Atrazine Post
		million acre			percent change		
Atrazine > 1.5 lb/a	Corn	11.09	-100.00	-100.00	-81.43	-52.97	54.08
	Sorghum	0.97	-100.00	-100.00	-100.00	15.79	-100.00
Atrazine < 1.5 lb/a	Corn	43.25	-100.00	-100.00	-100.00	-70.29	-100.00
	Sorghum	2.50	-100.00	-100.00	-44.17	0.99	39.98
Nicosulfuron	Corn	50.04	-56.21	0.38	-6.56	-21.31	-20.52
	Sorghum	0.00	0.00	0.00	0.00	0.00	0.00
Dicamba	Corn	65.19	9.80	6.46	3.20	-2.00	-19.31
	Sorghum	3.08	71.87	68.81	33.83	35.84	-21.78
Cyanazine	Corn	38.05	-100.00	9.64	10.91	26.59	-1.71
	Sorghum	0.06	-100.00	3272.90	3243.54	1216.23	1209.10
Bromoxynil	Corn	52.39	22.85	10.98	4.21	5.24	-4.79
	Sorghum	0.86	99.90	77.05	62.85	-26.30	-17.98
Bentazon	Corn	2.36	1702.44	236.04	233.06	569.35	329.40
	Sorghum	0.86	99.90	77.05	62.85	-26.30	-17.98
Metolachlor	Corn	29.82	79.70	20.90	20.92	20.84	2.80
	Sorghum	1.27	130.22	92.67	98.41	121.79	-8.78
EPTC	Corn	0.00	0.00	0.00	0.00	0.00	0.00
	Sorghum	0.00	0.00	0.00	0.00	0.00	0.00
Alachlor	Corn	26.03	89.64	37.01	37.04	35.87	17.41
	Sorghum	0.51	345.73	86.81	84.20	132.52	20.45
Simazine	Corn	7.82	-100.00	63.72	64.01	12.18	68.82
	Sorghum	0.00	0.00	0.00	0.00	0.00	0.00
Pendimethalin	Corn	2.16	-100.00	-10.21	-9.07	2.65	-52.80
	Sorghum	2.50	-100.00	-100.00	-44.20	0.99	39.98
Propachlor	Corn	0.16	-100.00	-100.00	-100.00	-100.00	-100.00
	Sorghum	0.21	992.15	876.04	876.04	314.38	316.87
Glyphosate	Corn	0.00	*	0.00	0.00	*	0.00
	Sorghum	0.00	1000.00	1000.00	105.59	100.29	-0.26
Butylate	Corn	2.33	1715.28	202.97	202.93	195.62	306.14
	Sorghum	0.00	0.00	0.00	0.00	0.00	0.00
2,4-D	Corn	13.62	264.12	28.46	38.84	8.73	-10.70
	Sorghum	2.04	98.78	80.46	54.57	19.45	-23.58

[a]Restriction of annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL.

[b]Maximum Contaminant Level (MCL) for atrazine is 3 parts per billion.

[c]Restriction of 24-hour acute concentration of atrazine in surface water to 10-day HAL.

[d]10-day Health Advisory Level (HAL) for atrazine is 100 parts per billion.

APPENDIX B. SHIFTS IN WEED CONTROL STRATEGIES

Table B.1. Percentage of corn acres treated, baseline

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
			percent
96	Atrazine[a]-Bladex preemergence	Accent-Banvel postemergence Accent-Buctril postemergence	16.4
240	Atrazine[a]-Bladex preplant inc.	Accent-Banvel postemergence Accent-Buctril postemergence	11.7
252	Atrazine[a]-Lasso preplant inc. Atrazine[a]-Dual preplant inc.	Accent-Banvel postemergence Accent-Buctril postemergence	9.5
141	Bladex-Lasso preplant inc. Bladex-Dual preemergence	Accent-Banvel postemergence Accent-Buctril postemergence	8.3
251	Atrazine[a]-Lasso preplant inc. Atrazine[a]-Dual preplant inc.	2,4-D postemergence Banvel-2,4-D postemergence	6.8
273	Princep preplant inc.	Accent-Banvel postemergence Accent-Buctril postemergence	5.7
239	Atrazine[b]-Bladex preplant inc.	2,4-D postemergence Banvel-2,4-D postemergence	4.2
15	Atrazine[b]-Lasso early preplant	Accent-Banvel postemergence Accent-Buctril postemergence	3.7
220	Rotary hoe and row cultivator	2,4-D postemergence Banvel-2,4-D postemergence	3.7

[a]Atrazine applied at a rate < 1.5 lb/acre.
[b]Atrazine applied at a rate > 1.5 lb/acre.

Table B.2. Percentage of corn acres treated, triazine ban

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
			percent
339	Dual.ppi & 2,4-D.post	Banvel.post Buctril.post Basagran.post	55.8
221	Rotary Hoe & Row Cultivator	Accent-Banvel.post Accent-Buctril.post	15.8
199	Dual.pre & Banvel.post	Accent-Banvel.post Accent-Buctril.post	7.9
164	Dual-Banvel.pre	2,4-D.post Banvel-2,4-D.post	5.8
340	Dual.ppi & 2,4-D.post	Banvel.post Buctril.post Basagran.post	3.4
222	Rotary Hoe & Row Cultivator	Accent-Banvel.post Accent-Buctril.post	3.0
488	Rotary Hoe & Row Cultivator	Accent-Banvel.post Accent-Buctril.post	2.3
486	Rotary Hoe & Row Cultivator	2,4-D.post Banvel-2,4-D.post	1.5
68	Roundup.epp & Banvel.post & Lassoor Dual.plt	2,4-D.post Banvel-2,4-D.post	1.5

Table B.3. Percentage of corn acres treated, atrazine ban

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
			percent
141	Bladex-Dual pre	Accent-Banvel post Accent-Buctril post	19.7
273	Princep preplant inc.	Accent-Banvel post Accent-Buctril post	13.1
261	Bladex preplant inc.	Accent-Banvel post Accent-Buctril post	13.0
339	Dual ppi & 2,4-D post	Banvel post Buctril post Basagran post	8.4
283	Bladex-Dual ppi	2,4-D post Banvel-2,4D post	8.0
221	Rotary hoe and row cult.	Accent-Banvel post Accent-Buctril post	7.6
285	Bladex-Dual ppi	Accent-Banvel post Accent-Buctril post	6.0
117	Bladex preemergence	Accent-Banvel post Accent-Buctril post	5.9
259	Bladex preplant inc.	2,4-D post Banvel-2,4-D post	2.1
220	Rotary hoe and row cult.	2,4-D post Banvel-2,4-D post	2.0

Table B.4. Percentage of corn acres treated under the scenario of restricting annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
			percent
141	Bladex-Dual pre	Accent-Banvel post Accent-Buctril post	19.7
261	Bladex ppi	Accent-Banvel post Accent-Buctril post	13.1
273	Princep ppi	Accent-Banvel post Accent-Buctril post	11.7
339	Dual ppi & 2,4-D post	Basabram post Banvel post Buctril post	8.4
283	Bladex-Dual ppi	2,4-D post Banvel-2,4-D post	8.0
285	Bladex-Dual ppi	Accent-Banvel post Accent-Buctril post	6.0
117	Bladex pre	Accent-Banvel post Accent-Buctril post	5.5
221	Rotary Hoe & Row Cultivator	Accent-Banvel post Accent-Buctril post	5.1
220	Rotary Hoe & Row Cultivator	2,4-D post Banvel-2,4-D post	3.7

Table B.5. Percentage of corn acres treated under the scenario of restricting 24-hour acute concentration of atrazine in surface water to 10-day HAL

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
			percent
141	Bladex-Dual pre	Accent-Banvel post Accent-Buctril post	22.5
236	Atrazine[b]-Bladex ppi	Atrazine[b]-Basagran post Atrazine[b]-Banvel post Atrazine[b]-Buctril post	10.1
339	Dual ppi & 2,4-D post	Banvel post Buctril post Basagran post	8.2
240	Atrazine[b]-Bladex ppi	Accent-Banvel post Accent-Buctril post	6.5
117	Bladex pre	Accent-Banvel post Accent-Buctril post	6.1
273	Princep ppi	Accent-Banvel post Accent-Buctril post	5.1
285	Bladex-Dual ppi	Accent-Banvel post Accent-Buctril post	4.5
283	Bladex-Dual ppi	2,4-D post Banvel-2,4-D post	4.4
261	Bladex ppi	Accent-Banvel post Accent-Buctril post	4.4
253	Bladex ppi	Atrazine[a] post	4.1
220	Rotary Hoe & Row Cult.	2,4-D post Banvel-2,4-D post	3.7
221	Rotary Hoe & Row Cult.	Accent-Banvel post Accent-Buctril post	2.0

[a]Atrazine applied at a rate < 1.5 lb/acre.

[b]Atrazine applied at a rate > 1.5 lb/acre.

Table B.6. Percentage of corn acres treated, atrazine post restriction

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
			percent
141	Bladex-Lasso preemergence Bladex-Dual preemergence	Accent-Banvel postemergence Accent-Buctril postemergence	14.7
339	Sutan preplant inc. & 2,4-D post Lasso preplant inc. & 2,4-D post Dual preplant inc. & 2,4-D post	Banvel postemergence Buctril postemergence Basagran postemergence	12.2
273	Princep preplant inc.	Accent-Banvel postemergence Accent-Buctril postemergence	11.5
221	Rotary hoe and row cultivator	Accent-Banvel postemergence Accent-Buctril postemergence	10.4
253	Bladex preplant inc.	Atrazine[a] postemergence	9.7
117	Bladex preemergence	Accent-Banvel postemergence Accent-Buctril postemergence	8.8
275	Bladex-Lasso preplant inc. Bladex-Dual preplant inc.	Atrazine[a] postemergence	8.1
263	Princep preplant inc.	Atrazine[a] postemergence	2.5

[a]Atrazine applied at a rate > 1.5 lb/acre.

Table B.7. Percentage of sorghum acres treated, baseline

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
			percent
1061	Prowl-Atrazine[a] postemergence	None	20.8
1072	Rotary hoe and row cultivator	2,4-D postemergence Banvel-2,4-D postemergence	16.8
1143	Rotary hoe and row cultivator	Prowl-Atrazine[a] postemergence	13.1
1069	Rotary hoe and row cultivator	Banvel postemergence Buctril postemergence Basagran postemergence	12.8
1074	Atrazine[a] preplant inc.	2,4-D postemergence Banvel-2,4-D postemergence	10.8
1078	Atrazine[a]-Dual preplant inc	Prowl-Atrazine[a] postemergence	8.8
1076	Atrazine[a]-Dual preplant inc.	Banvel-2,4-D postemergence	4.0

[a]Atrazine applied at a rate < 1.5 lb/acre.

Table B.8. Percentage of sorghum acres treated, triazine ban

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
			percent
1056	Ramrod.pre & Banvel.post	2,4-D.post Banvel-2,4-D.post	25.5
1072	Rotary Hoe & Row Cultivator	2,4-D.post Banvel-2,4-D.post	21.3
1055	Ramrod.pre & Banvel.post	2,4-D.post Banvel-2,4-D.post	17.7
1070	Rotary Hoe & Row Cultivator	Banvel.post Buctril.post Basagran.post	11.7
1069	Rotary Hoe & Row Cultivator	Banvel.post Buctril.post Basagran.post	11.6
1014	Banvel-2,4-D.post & Dual.plt	Banvel.post Buctril.post Basagran.post	4.7
1015	Banvel-2,4-D.post & Dual.plt	Banvel.post Buctril.post Basagran.post	4.3
1016	Banvel-2,4-D.post & Dual.plt	2,4-D.post Banvel-2,4-D.post	3.1

Table B.9. Percentage of sorghum acres treated, atrazine ban

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
			percent
1034	Bladex-Ramrod pre	2,4-D post Banvel-2,4-D post	37.1
1087	Dual ppi and Banvel post	Banvel post Buctril post Basagram post	14.9
1088	Dual ppi and Banvel post	2,4-D post Banvel-2,4-D post	13.6
1097	Dual ppi and 2,4-D post	2,4-D post Banvel-2,4-D post	13.0
1069	Rotary hoe and row cult.	Banvel post Buctril post Basagran post	12.1
1072	Rotary hoe and row cult.	2,4-D post Banvel-2,4-D post	3.6
1056	Dual pre and Banvel post Ramrod pre and Banvel post	2,4-D post Banvel-2,4-D post	2.2
1086	Dual ppi and Banvel post	Banvel post Buctril post Basagran post	2.1

Table B.10. Percentage of sorghum acres treated under the scenario of restricting annual average (over 4 quarters) of 24-hour acute concentration of atrazine in surface water to MCL

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
			percent
1034	Bladex-Ramrod pre	2,4-D post Banvel-2,4-D post	36.3
1087	Dual ppi & Banvel post	Banvel post Buctril post Basagram post	14.5
1093	Dual ppi & 2,4-D post	Prowl-Atrazine[a] post	12.7
1069	Rotary Hoe & Row Cult.	Banvel post Buctril post Basagram post	12.0
1045	Atrazine[a]-Dual pre	Prowl-Atrazine[a] post	9.1
1084	Dual ppi & Banvel post	Prowl-Atrazine[a] post	4.6

[a]Atrazine applied at a rate > 1.5 lb/acre.

Table B.11. Percentage of sorghum acres treated under the scenario of restricting 24-hour acute concentration of atrazine in surface water to 10-day HAL

Strategy Number	Primary Strategy	Secondary Strategy	Acres Treated
1121	Atrazine[b]-Dual pre	Prowl-Atrazine[b] post	22.8
1024	Atrazine[a] pre	2,4-D post Banvel-2,4-D post	20.4
1085	Dual ppi & Banvel post	Prowl-Atrazine[b] post	19.5
1034	Bladex-Ramrod pre	2,4-D post Banvel-2,4-D post	13.6
1069	Rotary Hoe & Row Cult.	Banvel post Buctril post Basagran post	11.4
1072	Rotary Hoe & Row Cult.	2,4-D post Banvel-2,4-D post	3.4
1088	Dual ppi & Banvel post	2,4-D post Banvel-2,4-D post	3.3
1056	Dual pre & Banvel post Ramrod pre & Banvel post	2,4-D post Banvel-2,4-D post	2.1

[a]Atrazine applied at a rate < 1.5 lb/acre.

[b]Atrazine applied at a rate > 1.5 lb/acre.

Table B.12. Percentage of sorghum acres treated, atrazine post restriction

Strategy Number	Primary Strategy	Secondary Strategy	Treated
			percent
1061	Prowl-Atrazine[a] postemergence	None	21.7
1143	Rotary hoe and row cultivate	Prowl-Atrazine[a] postemergence	18.7
1034	Bladex-Ramrod preemergence	2,4-D postemergence	13.9
1069	Rotary hoe and row cultivate	Banvel postemergence Buctril postemergence Basagran postemergence	13.1
1085	Lasso preplant inc. & Banvel post	Prowl-Atrazine[a] postemergence	9.2
1137	Prowl-Atrazine[a] postemergence	None	7.3
1093	Lasso preplant inc. & 2,4-D post Dual preplant inc. & 2,4-D post	Prowl-Atrazine[a] postemergence	7.2

[a]Atrazine applied at a rate < 1.5 lb/acre.

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